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High-performance, highly-resonant graded quantum well structures were developed under this grant and were successfully applied to direct, electrically-pumped generation of Terahertz-frequency radiation. Additionally, coupled quantum well structures were developed for producing quantum interference of intersubband transitions as a possible step toward lasing without inversion. Special highlights of the research were 1) the generation of continuous, electrically excited Terahertz radiation emission as well as pulsed, optically excited Terahertz radiation emission from highly resonant parabolic quantum wells and 2) the first achievement of increased transparency in intraband quantum well infrared optical absorption as a result of quantum interference among intraband quantum well optical transitions.

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1. COVER SHEET:

FINAL TECHNICAL REPORT

AFOSR GRANT F49620-94-1-0158

High Performance Graded Quantum Structures: Growth, Applications, Phenomena

February 15, 1998

Arthur C. Gossard, Principal Investigator

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2. INTRODUCTION

The principal objectives of the research under this grant were 1) the development of high-performance, highly resonant graded quantum well structures and their application to generation of Terahertz-frequency radiation and 2) the development of coupled quantum well structures for producing quantum interference of intersubband transitions as a possible step toward lasing without inversion.

There is a strong need for more powerful and tunable sources of radiation in the Terahertz frequency regime. Parabolically graded quantum wells form a highly resonant confinement system for electrons, and electrons can emit and absorb radiation at sharply engineerable frequencies in these quantum wells, with the resonant frequencies being essentially independent of filling of the quantum wells, independent of the intensity of excitation of the wells, and independent of electric fields across the wells for purely parabolic wells. We worked to take advantage of the opportunities presented by these properties in order to build new, simple, high-performance Terahertz radiation sources. A further goal was the development of modified versions of these radiation sources that will have strongly voltage-tunable emission wavelengths.

Our work on quantum interference in coupled quantum well intersubband transitions was a relatively new effort. Recently, an entirely new class of optical devices has been proposed based on interference between intersubband transitions in semiconductor quantum wells. These infrared devices include an intersubband laser that operates without a population inversion, and efficient non-linear optical elements, all of which rely on a destructive interference between intersubband transitions to sharply reduce the rate of absorption. Scattering events, which can dephase electrons in the double quantum well structure, tend to wash out the interference effects central to the device operation. It was the purpose of the present research to gain an understanding of scattering processes in single and coupled quantum wells, and to use that understanding to fabricate double quantum well structures for the observation of quantum interference effects.

3. PRINCIPAL RESULTS OF RESEARCH EFFORT:

The principal results of the research were 1) the generation of continuous, electrically excited Terahertz radiation emission as well as pulsed, optically excited Terahertz radiation emission from highly resonant parabolic quantum wells and 2) the first achievement of increased transparency in intraband quantum well infrared optical absorption as a result of quantum interference among intraband quantum well optical transitions.

A. Graded quantum well structures and their application to generation of Terahertz-frequency radiation:

- **Electrically pumped Terahertz emitters:**

We have observed grating coupled far infrared (FIR) emission from parabolically graded quantum wells (PQWs) by the application of an in-plane electric field. One of the most interesting features of parabolically confined potentials is that they will absorb long-wavelength light only at the bare harmonic oscillator frequency ω_o, independent of the number of electrons in the well (i.e. independent of the electron-electron interaction).[1] This can be considered as a generalization of Kohn's theorem which states that cyclotron resonance absorption is unaffected by electron-electron interactions.[2] The bare harmonic oscillator frequency for PQWs is given by

$$\omega_o = \sqrt{\frac{8\Delta}{L^2 m^*}} \qquad (1)$$

where Δ is the energetic depth of the well, L is the well width, and m* is the effective mass. The generalized Kohn's theorem has been confirmed for FIR absorption in PQWs.[3] In our new work, we have shown that, in agreement with the generalized Kohn's theorem, PQWs will emit FIR radiation at the designed harmonic oscillator frequency when the electron distribution is heated.

For this study, two samples were grown by molecular beam epitaxy on semi-insulating substrates. A schematic band diagram of the general structure used for each sample is shown in Figure 1. The layer structure for the 2000 Å PQW sample is as follows: 2000 Å $Al_{0.3}Ga_{0.7}As$ buffer / 100 period smoothing superlattice (14 Å GaAs / 6 Å AlAs) / 4 delta doping sheets (total 8 x 10^{11} cm^{-2}), each separated by 10 Å of $Al_{0.3}Ga_{0.7}As$ / 100 Å $Al_{0.3}Ga_{0.7}As$ spacer / 2000 Å PQW with x=0.2 at the edges / 100 Å $Al_{0.3}Ga_{0.7}As$ spacer / 4 delta doping sheets (5 x 10^{11} cm^{-2} total) each separated by 10 Å $Al_{0.3}Ga_{0.7}As$ / 17 delta doping sheets (1 x 10^{12} cm^{-2} total) each separated by 10 Å $Al_{0.3}Ga_{0.7}As$ / 800 Å $Al_{0.3}Ga_{0.7}As$ / 100 Å GaAs cap. The layer structure for the 760 Å PQW sample is as follows: 2000 Å GaAs buffer / 300 period smoothing superlattice (14 Å GaAs / 6 Å AlAs) / one delta doping sheet of 5 x 10^{11} cm^{-2} / 200 Å $Al_{0.3}Ga_{0.7}As$ spacer / 760 Å PQW (x=0.1 at the edges) / 200 Å $Al_{0.3}Ga_{0.7}As$ spacer / 2 delta doping sheets (5 x 10^{11} cm^{-2} total) separated by 20 Å $Al_{0.3}Ga_{0.7}As$ / 26 delta doping sheets (5.2 x 10^{12} cm^{-2} total)

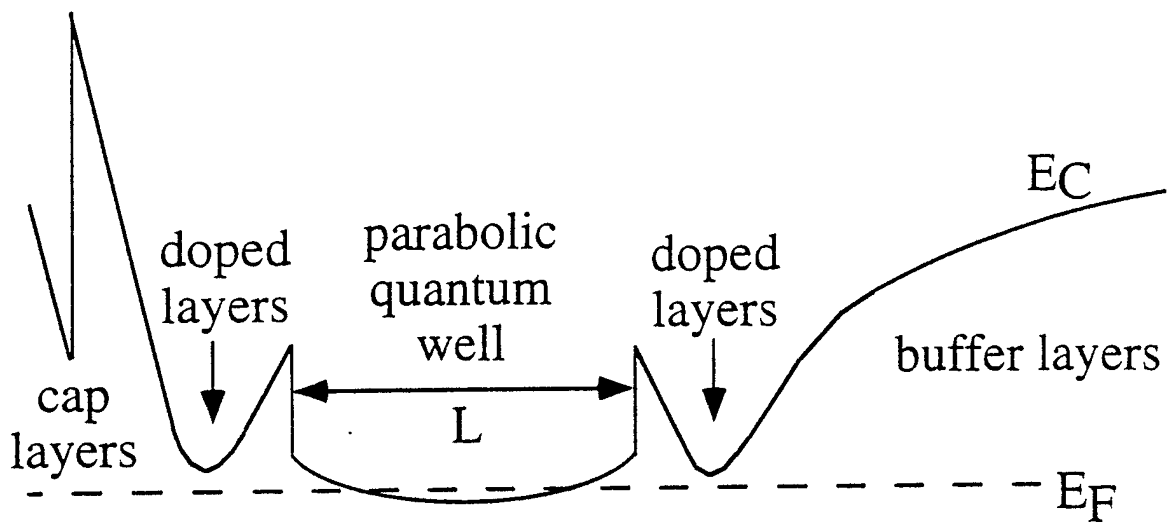


FIG. 1 Schematic band diagram of the general structure for both samples. The growth direction is to the left.

separated by 20 Å $Al_{0.3}Ga_{0.7}As$ / 100 Å GaAs cap. Each parabolic well was grown using the digital alloy technique[4] with 20 Å periods.

Standard Hall measurements were performed on both wells in the van der Pauw configuration. The low temperature (10 K) carrier concentration and mobility for the 2000 Å well are 2.7 x 10^{11} cm^{-2} and 120,000 cm^2/Vs, respectively, and for the 760 Å well they are 3.9 x 10^{11} cm^{-2} and 170,000 cm^2/Vs.

The final device geometry is shown in Figure 2. Standard AuGe ohmic contacts were made as large stripes 5 mm apart. Then a metallic grating (50 Å Cr / 2000 Å Au) was deposited parallel to the ohmic contact stripes to act as the grating coupler (The grating coupler is necessary to couple light out normal to the surface, since intersubband transitions are allowed only for light polarized perpendicular to the layers. Also, edge emission is much weaker due to self absorption.) Following Helm et al., who found that the optimal coupling was achieved when the grating period was slightly smaller (~10%) than the wavelength of emitted radiation in air,[5] we used 50 μm and 20 μm grating periods for the 2000 Å and 760 Å wells, respectively. The duty cycle was 50% for each grating.

To measure the FIR radiation from the PQWs, the emitter was placed at one end of a metallic light pipe with a lightly doped (6 x 10^{13} cm^{-3}) n-InSb photoconductive detector at the other end. The entire light pipe is immersed in liquid helium to obtain 4 K background conditions. The emitter and detector are separated by 20 cm, and the detector sits in a superconducting magnet. The n-InSb photoconductive detector is biased with a constant current and operated in the cyclotron resonance mode. The spectral width of the cyclotron resonance photoconductive response[6] is about 3 cm^{-1}. By tuning the magnetic field, the spectral sensitivity can be changed according to the cyclotron resonance frequency $\omega_c = eB/m^*$ (where B is the magnetic field and e is the electronic charge) resulting in a tuning constant of about 65 cm^{-1} per Tesla. The emission spectra data are actually a convolution of the true emission spectra and the detector response. But the linewidth of the detector response (about 3 cm^{-1}) is narrower than the linewidth of the emitted radiation from the PQWs (see below), so the linewidth of observed spectra is limited by the true emission linewidth.

Figure 3(a) shows the emission spectra obtained for the 2000Å PQW. The peak frequency of the FIR emission is approximately 52 cm^{-1}, in good agreement with the designed harmonic oscillator frequency of 47 cm^{-1}. Also, the peak emission frequency does not change as the input power is varied. The linewidth also remains essentially constant at 18 cm^{-1} for various input powers. The peak intensity increases approximately linearly as the electric field is increased up to 8 V/cm, and above 10 V/cm the emission intensity saturates.

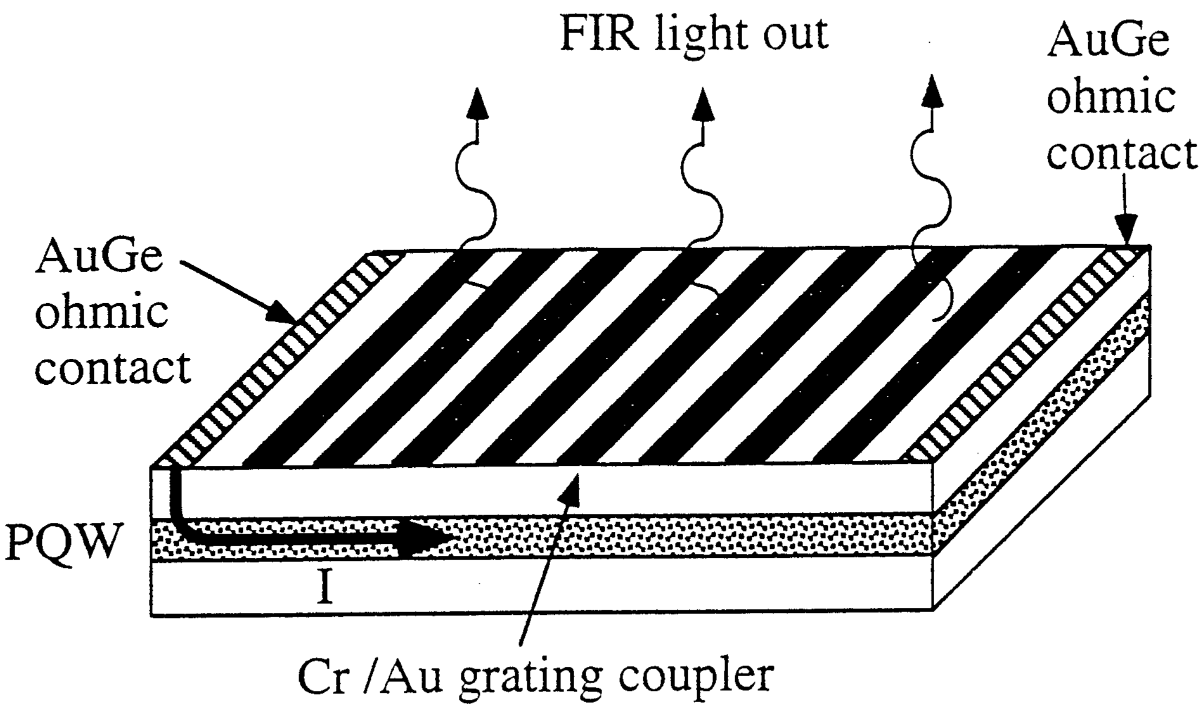


FIG. 2 Device geometry for PQW emitter structures. The radiating area is approximately 5 x 5 mm^2.

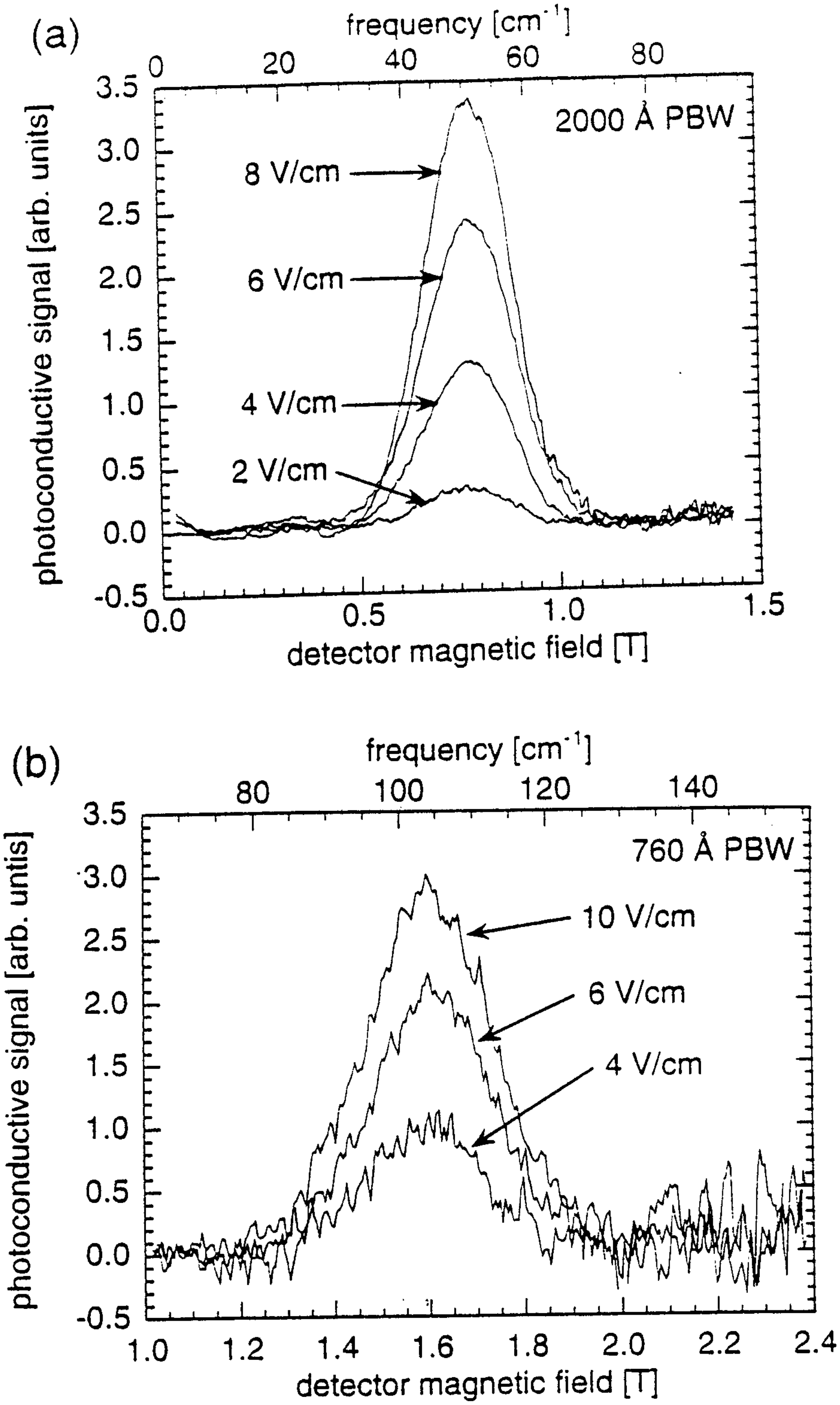


FIG. 3 Emission spectra for different in-plane electric fields for the 2000 Å PQW (a) and the 760 Å PQW (b). The frequency axis (top abscissa) is simply the detector magnetic field multiplied by the cyclotron resonance tuning of the photoconductive detector (65 cm^{-1} per Tesla).

To estimate the output power from the 2000 Å PQW, we compare its emission with the cyclotron resonance emission at 0.8 T (i.e. ~ 52 cm^{-1}) from a lightly doped (6 x 10^{13} cm^{-3}) n-InSb emitter for which the emission power is known.[7] This comparison yields an order of magnitude estimate of 7 x 10^{-9} W emitted from the 2000 Å PQW sample at an electric field of 8 V/cm. This result can be compared with a rough theoretical estimate based on the intersubband lifetimes. The electrical input power P_{in} is simply multiplied by the grating coupling efficiency η_g and the ratio of the non-radiative lifetime τ_{nr} to the radiative lifetime τ_{rad} (for $\tau_{nr} << \tau_{rad}$).

$$P_{out} = P_{in}\eta_g \frac{\tau_{nr}}{\tau_{rad}} \qquad (2)$$

The non-radiative intersubband lifetime for energies below the optical phonon energy was measured to be ~ 1 ns in a coupled quantum well structure by Heyman *et al.* [8] The radiative lifetime for a classical electron oscillator is given by

$$\tau_{rad} = \frac{3\varepsilon_0 m^* c\lambda_0^{\,2}}{2\pi e^2} \qquad (3)$$

where ε_0 is the permittivity of free space, c is the speed of light, and λ_0 is the wavelength. At $\lambda_0 = 200$ µm, $\tau_{rad} = 1.1 \times 10^{-4}$ s. The average electrical input power is 40 mW and assuming a grating coupling efficiency of 5%, $P_{out} = 1.8 \times 10^{-8}$ W which is within an order of magnitude of the experimental result. We estimate the temperature of the electron distribution to be ~ 30 K from the data of Hirakawa *et al.* [9] showing the electron temperature as a function of power input per electron for a two dimensional system.

The emission spectra for the 760 Å PQW are shown in Fig. 3(b). Again, the peak emission frequency at 104 cm^{-1} agrees well with the designed frequency of 97 cm^{-1}. (The increased noise in Fig. 3(b) is due solely to the larger noise of the photoconductive detector at higher magnetic fields.) As in the case of the 2000 Å PQW, the linewidth for each spectrum is ~18 cm^{-1}.

We have thus shown that the grating-induced FIR emission from PQWs occurs at the bare harmonic oscillator frequency even though the wells are heavily populated with electrons, in accordance with the generalized Kohn's theorem. Compared to previous electrically pumped FIR emitters, this source has the attractive features that the emission spectrum is concentrated at a single frequency and the emission is obtained without the need for a magnetic field. Since the resonant frequency is simply proportional to (and designable with) the curvature of the well, we anticipate the possibility of a voltage tunable FIR emitter in which the curvature of the well is varied in the growth direction. The electron gas position in the well could be tuned by applying a bias between a front gate and back gate. This concept has already been demonstrated for the absorption case by observation of linearly tunable absorption in a logarithmically graded well.[10] We also expect that the emission intensity can be significantly improved by employing multiple PQWs and by vertically injecting electrons resonantly into higher energy levels, analogously to the resonant vertical injection in superlattices by Helm et al.[11]

- **Electrically pumped Terahertz emitters with vertical injection:**

Initial experiments on the vertical injection of electrons have been successfully carried out. Structures for measurement of the electrical characteristics under tunnel injection into a parabolic quantum well were made and studied, and structures with three and ten parabolic wells for measurement of Terahertz radiation emission were fabricated and studied.

The I-V characteristics of a single parabolic well under tunnel injection from adjacent n-doped layers are shown in Figure 4. The spectra exhibit an extensive sequence of periodic maxima in dI/dV associated with resonant tunneling into the uniformly spaced sequence of parabolic quantum well energy levels.

The sample design of the vertically injected ten-well structure is shown in Figure 5, the spectra of emitted radiation are shown in Figures 6 and 7. The spectra exhibit a strong, wide emission near 90 cm-1 associated with the fundamental interlevel energy separation of adjacent parabolic quantum well energy levels. In addition, several sharp emission lines are seen at higher frequencies. The origin of these lines is still not entirely clear and is under investigation. The three-well vertically-injected structure shows similar behavior.

- **Optically pumped Terahertz pulse emitters:**

We have also made substantial advancements in production of few-cycle THz emission from semiconductors excited by ultrafast laser pulses. In order to improve the THz emission and to investigate the dynamic response of a quasi two dimensional electron gas we have designed and grown structures with a parabolic well just beyond the depletion zone of a n-doped GaAs cap layer as shown in Figure 8. From electrons in modulation doped wells we expect much longer damping times than from electrons in uniformly doped materials. According to Kohn´s theorem the electrons in parabolically confined potentials will interact with

single parabolic quantum well
resonant tunneling diode:

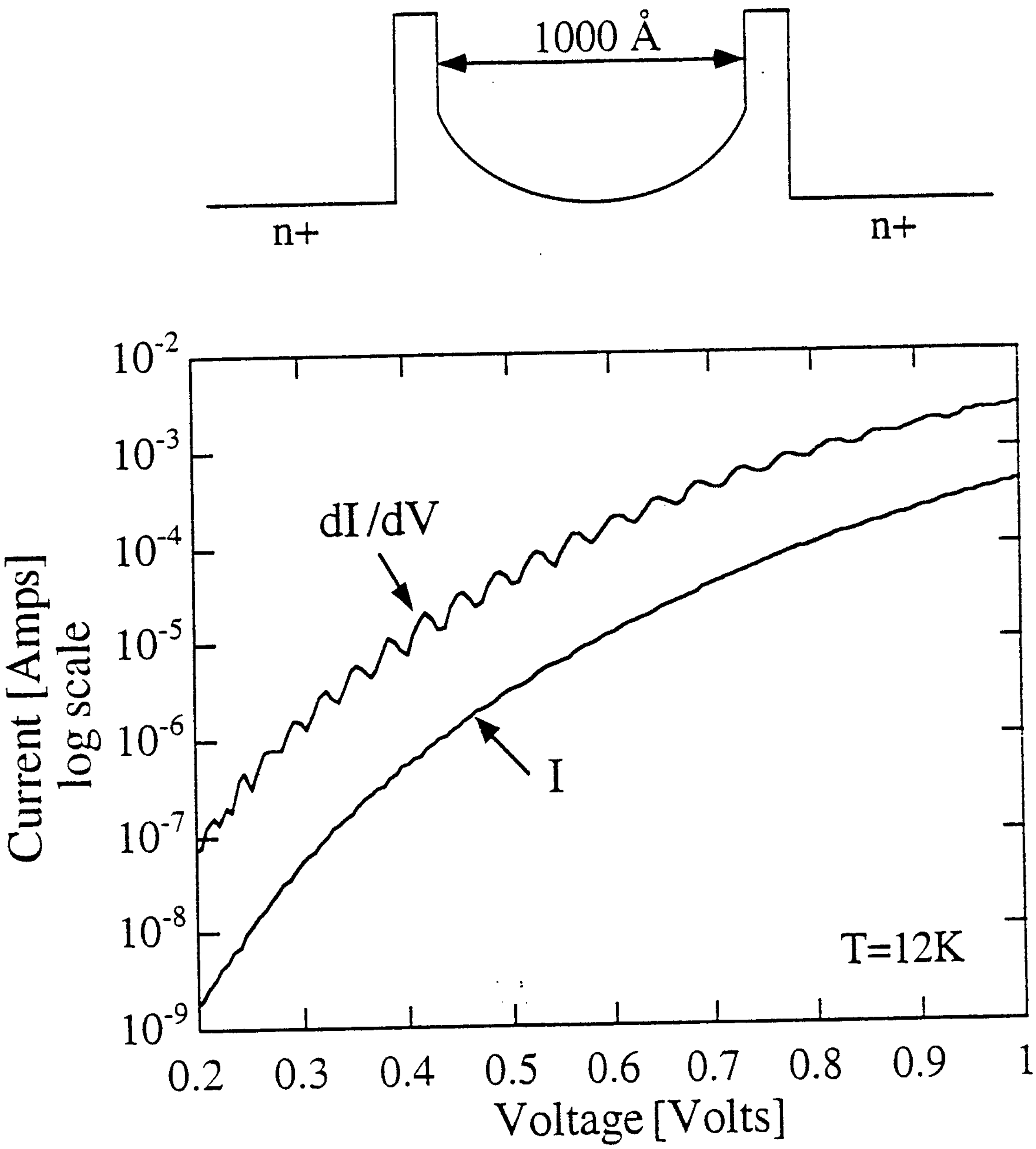


FIG. 4 Resonant tunneling in a single parabolic quantum well.

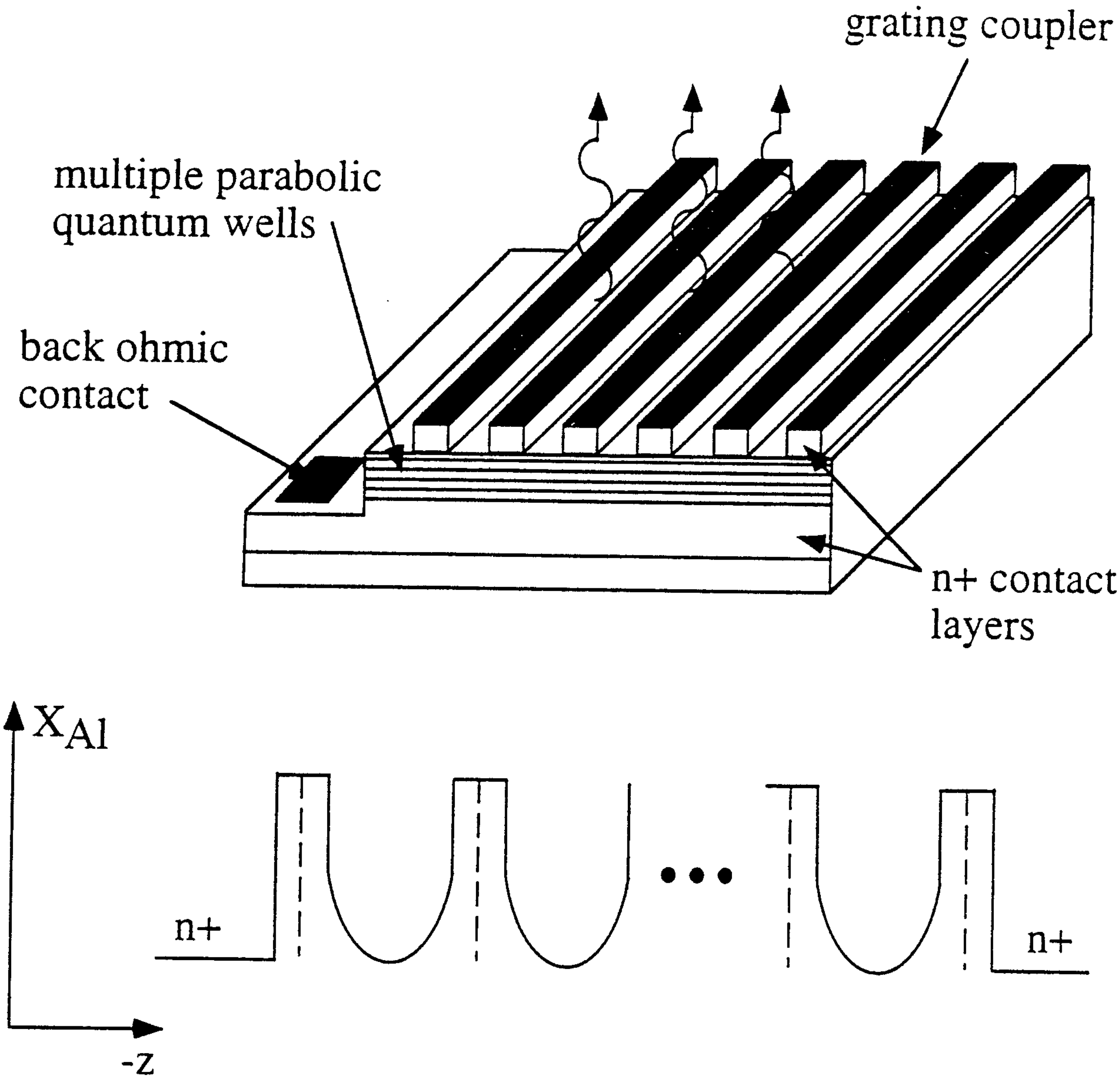


FIG. 5 Structure of the 10 well emission sample.

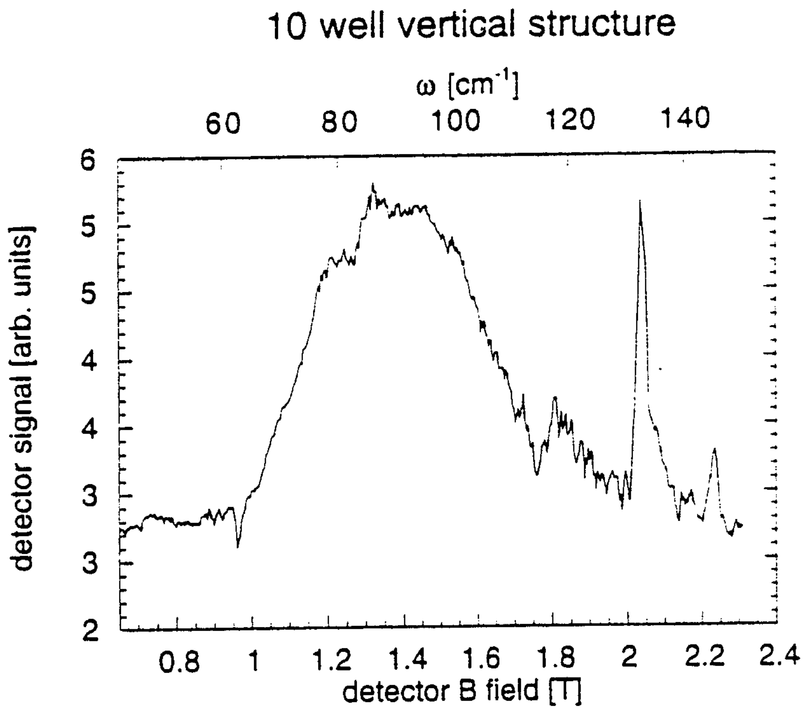


FIG. 6 Emission from the 10 well sample.

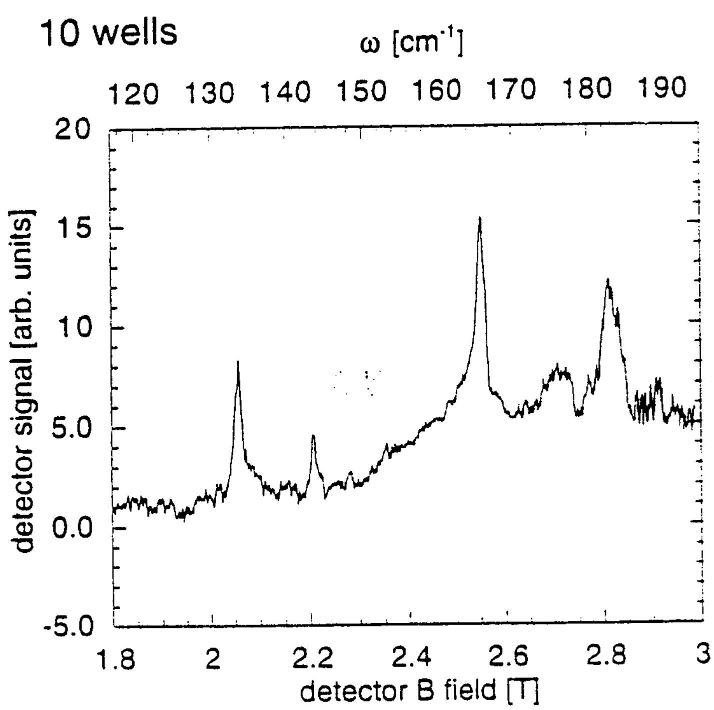


FIG. 7 Emission from the 10 well sample.

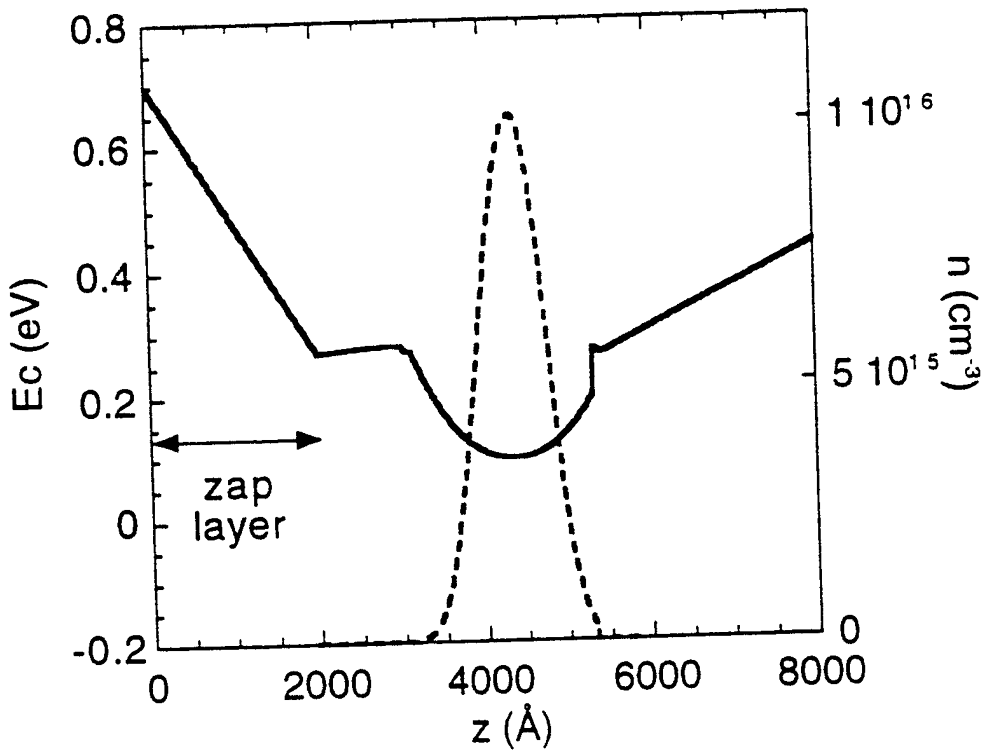


FIG. 8 Schematic band diagram of the parabolic well and of the top GaAs layer for photoexcitation.

light only at the bare harmonic oscillator frequency $\omega_0 = \sqrt{\frac{\quad}{L^2 m^*}}$ (Δ is the depth of the parabolic potential, L the width, and m* the effective mass) independent of the carrier concentration in the well. The parabolic well was designed to be 2000Å wide and to have a resonance frequency ω_0 of about 1.5 THz. The structure was modulation doped to give an electron concentration in the well of about $5 \cdot 10^{11}$ cm^{-2}. In experiments on a similar parabolic well where the electrons where heated by a lateral current spontaneous THz emission was observed at the expected resonance positions as described above.[12]

The optical excited experiments were performed using a mode-locked Ti:Sapphire laser emitting 100 fs pulses at 800 nm. A 4.2 K bolometer is used to detect the THz radiation. Time resolution is achieved by focusing two delayed pulses on the samples and by recording the time integrated THz auto correlation signal as a function of the delay time.

Coherent THz emission from the parabolic well sample was obtained at room temperature. The auto correlation signal and the Fourier transformed spectra are shown in Fig. 9 and 10 for different excitation densities. Clear oscillations are visible with a damping time corresponding to the high DC mobility of the quasi two dimensional channel. The observed frequency is around 1.5 THz and is only weakly dependent on filling of the parabolic well by the photoexcited carriers (in sharp contrast to the frequencies from bulk materials). According to the generalized Kohn´s theorem we do not expect a dependence of the emission frequency on the carrier excitation density.

THz emission from the parabolic well sample can also be observed when the sample is excited by a few-cycle THz pulse which is generated by excitation of coherent plasma oscillations in bulk n-doped GaAs. (The bulk n-doped GaAs is excited by a femtosecond Ti:Sapphire laser.) The few-cycle THz beam is transmitted through the parabolic well sample mounted in a helium flow cryostat. Time resolution is achieved by mixing the transmitted THz signal with a second THz beam and detecting the superposition with a 4 K bolometer.

Figure 11 (a) shows the time-resolved THz pulse after transmission through the parabolic well sample. The first part of the signal ($t < 1.5$ ps) shows mainly the exciting THz pulse which has a center frequency of about 1.5 THz. At longer delay times, the dielectric response of the electrons in the parabolic well becomes visible. According to Kohn's theorem, the electrons in the parabolically confined potential interact with light only at the bare harmonic oscillator frequency. The observed oscillations agree with the calculated intersubband transition frequency of about 1.8 THz and show the free induction decay of the polarization of the collective electron intersubband mode. The transients in Figure 11 (b) are magnifications of these oscillations recorded at different temperatures.

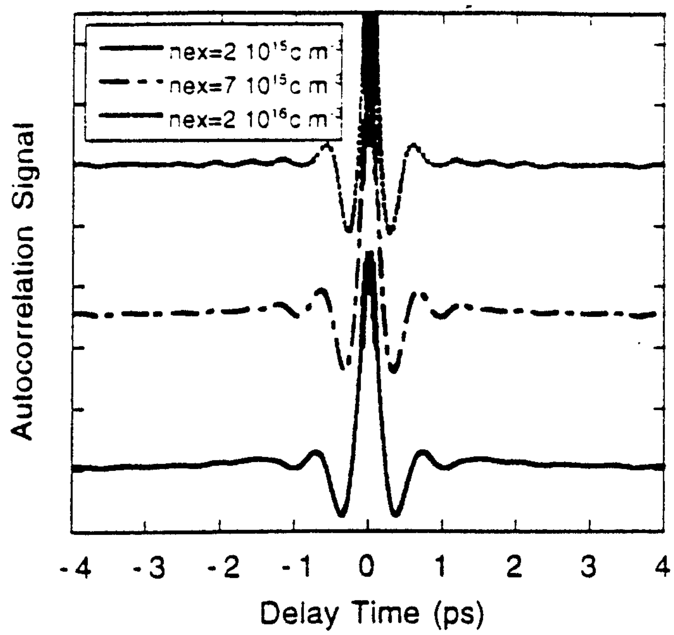


FIG. 9 Auto correlation of the THz emission from the parabolic well.

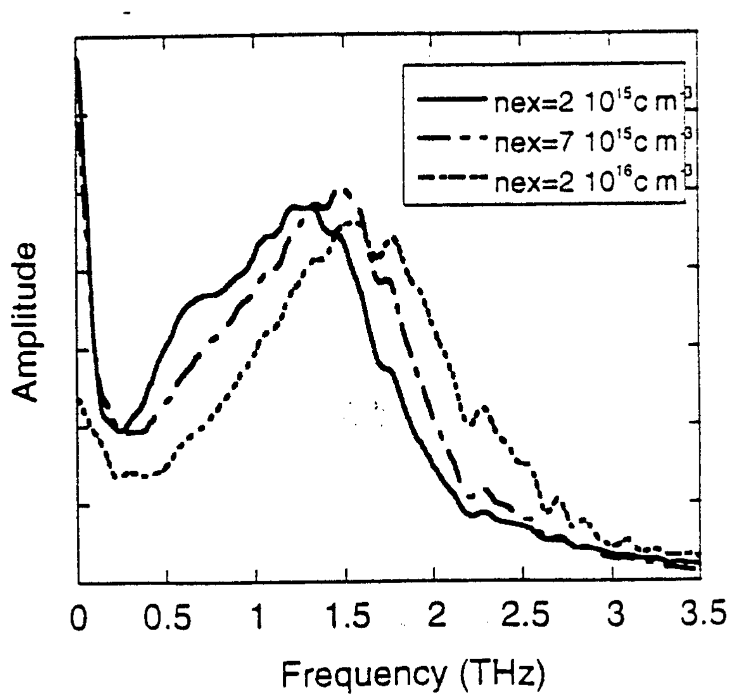


FIG. 10 Fourier transformed spectra of the optical excited THz emission from the parabolic well.

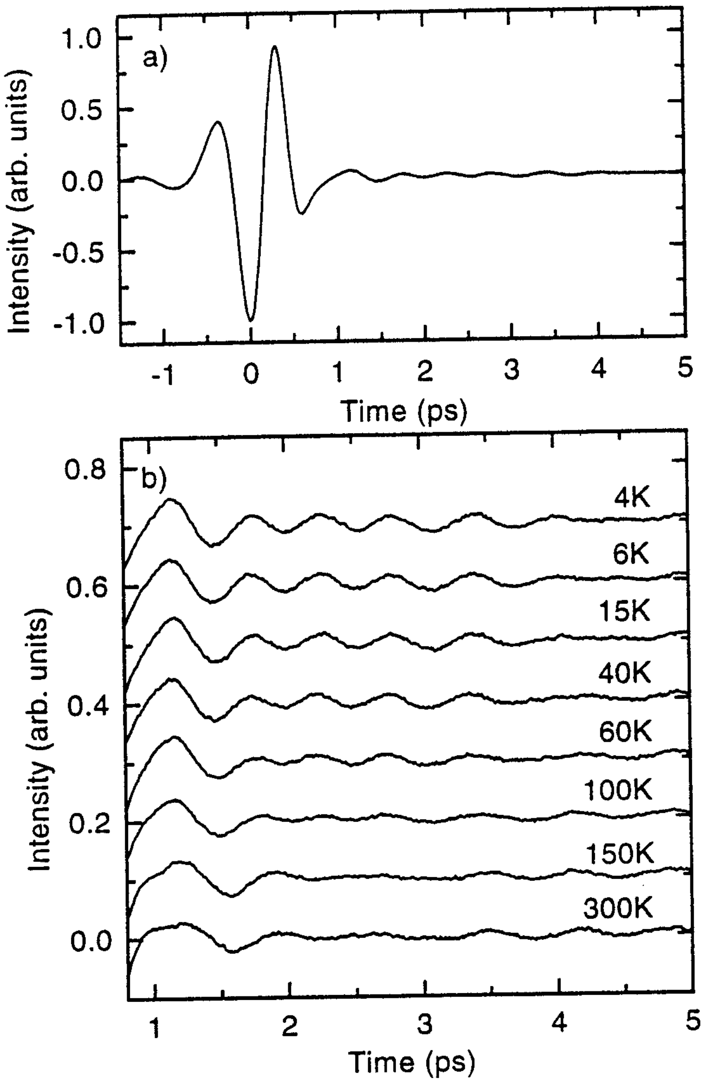


FIG 11 a) Time-resolved THz pulse after transmission through the parabolic quantum well. b) Magnification of the free induction decay recorded at different temperatures.

B. Coupled quantum well structures for quantum interference of intraband transitions:

In this work, we achieved the first tunneling-induced transparency in coupled quantum well structures. The transparency is produced by interference between intersubband transitions of coupled quantum wells.

An entirely new class of optical devices has recently been proposed based on such interference between intersubband transitions in coupled quantum wells. These proposed infrared devices include an intersubband laser that operates without a population inversion, and efficient non-linear optical elements, which rely on a destructive interference between intersubband transitions to sharply reduce the rate of absorption[13].The success of these devices depends heavily on the scattering rates of electrons during the intersubband processes. The purpose of the present work is to further the understanding of intersubband transition scattering, and to develop semiconductors for the observation of quantum interference effects, and the possible construction of optical devices based on those effects.

The most direct application of intersubband interference phenomena is for semiconductor lasers which do not require a population inversion. In a standard laser system where emission and absorption probabilities for the lasing transition are equal, a population inversion (i.e. more electrons in the excited state than the ground state) is necessary to achieve gain. If it is possible to force an asymmetry in the emission and absorption probabilities by decreasing the likelihood of absorption and increasing the likelihood of emission, a population inversion is no longer necessary for lasing. This idea was first proposed for a four-level atomic system[14], and soon after generalized for more readily available and experimentally achievable atomic systems[15]. Initially, the reduction of absorption as a result of destructive interference was observed in atomic experimentally[16]. Recently, lasing without inversion has been observed in atomic systems[17,18].

The combination of the research areas of intersubband transitions in semiconductor quantum wells and lasing without inversion in atomic systems was initially proposed by Imamoglu and Ram[19]. Previous attempts to observe amplification without inversion relied on atomic systems with parameters such as energy levels and decay rates fixed by nature. The proposed semiconductor structure utilizes bandgap engineering to artificially fabricate a three-level lasing system in which the energy levels and decay rates can now be controlled by simply adjusting the quantum well growth parameters. Another advantage of a semiconductor system is that the coupling of the upper levels occurs through coherent resonant tunneling across a barrier, instead of via an electromagnetic field, removing the need for a coupling laser.

However, there is an important disadvantage to the semiconductor scheme. Atomic systems, although inflexible, present a nearly ideal system with regard to phase randomizing collisions which can destroy interference effects. Dephasing rates can be negligibly small compared to other relevant rates such as the decay rate to the continuum and the frequency of the coupling laser. In contrast, electrons in a semiconductor are embedded in a crystal lattice, and are therefore subject to more scattering events. Scattering times from crystal imperfections and from the emission of optical and acoustic phonons can be quite short, with possible detrimental effects on the interference phenomena. In the first part of our work, we sought to understand these scattering and dephasing times, which then enable the design of a resonant tunneling induced transparency structure.

- **Experiment**

All of the samples for the study of the scattering and dephasing times were grown by molecular beam epitaxy on semi-insulating GaAs substrates. The digital alloy technique[4] was used for growth of the undoped spacers surrounding the quantum wells. The digital alloy is effective because the electron wavelengths are much larger than the superlattice period (20Å), so the electron feels an average potential of the superlattice which is designed to simulate an analog alloy of the desired composition. The digital alloy provides the smoothing effects of a superlattice as well as giving access to a large range of alloy compositions with a single aluminum furnace setpoint. This is especially important in the growth of some of the coupled quantum wells used in this study where as many as four different alloy compositions were used in the same growth. Growth interrupts of 10-20 seconds were used at each quantum well interface to allow significant smoothing at the interfaces due to the adatom migration on the growth surface[20].

Absorption spectra were measured with a Bruker IFS 66V Fourier Transform Infrared (FTIR) spectrometer. For all samples measured, we have used the waveguide or multipass geometry. In this configuration (see figure 1), light is incident on a facet polished at 45° with respect to the growth direction, and after several bounces leaves the sample through another 45° facet and is detected by a HgCdTe liquid nitrogen cooled detector. This configuration has the advantages of providing a component of electric field in the growth direction to excite the intersubband transitions, as well as increasing the absorption strength with multiple passes through the active region. The Schottky gate on the surface of the sample is used to deplete the quantum wells to obtain a reference spectrum, and also to apply varying fields across the quantum wells. Another technique for producing a reference spectrum is based on using a linear polarizer to create a TE or TM linearly polarized incident beam. Only the TM beam has a component of electric field in the growth direction needed to excite the intersubband transitions, so the TM beam gives the sample spectrum and the TE beam gives a reference spectrum.

- **Results and Discussion**

a. Absorption in coupled quantum wells

In order to understand the coupling strength of the upper two levels, the first set of experiments used samples in which the upper levels are bound states, rather than states that are quasi-bound to a continuum on one side via a tunneling barrier. In the bound state case, there are no quantum interference effects to be included in the analysis, since there is no tunneling coupling to a continuum.

The first structure used a very narrow 20Å GaAs quantum well to align the ground state of this narrow well with the first excited state of a wider 90Å GaAs quantum well as shown in figure 12(a). For this type of sample only a single absorption line was observed (see figure 12(b)), even as the gate voltage was varied over as large a range as possible in an attempt to pull the levels into resonance. Additionally a range of tunneling barriers between wells from 25Å to 40Å was used. The absence of a second peak in the absorption spectra comes from the strong dephasing resulting from interface roughness scattering in the 20 Å GaAs quantum well where even single monolayer fluctuations are a significant fraction of the total well width. If dephasing rates exceed the tunneling rates between wells, we would no longer expect a coherent superposition of states. Instead, states would be strongly localized in the individual wells, resulting in a single absorption peak, as observed.

In a separate study of intersubband absorption in single quantum wells of different well widths and alloy compositions[21], it was found that the absorption linewidth was consistent with broadening dominated by interface roughness. It was also found that the linewidth was relatively unaffected by alloy composition in the quantum well, for a constant well width. Therefore, the narrow 20Å GaAs well can then be replaced with a wider, alloyed $Al_xGa_{1-x}As$ well while keeping the same energy level configuration.

This second technique was employed in the structure shown in figure 13. This sample (sample A) was a multi-quantum well stack with n+ contact layers above and below the quantum wells. For performing absorption experiments, the TM vs. TE referencing technique described above was used since a Schottky gate is

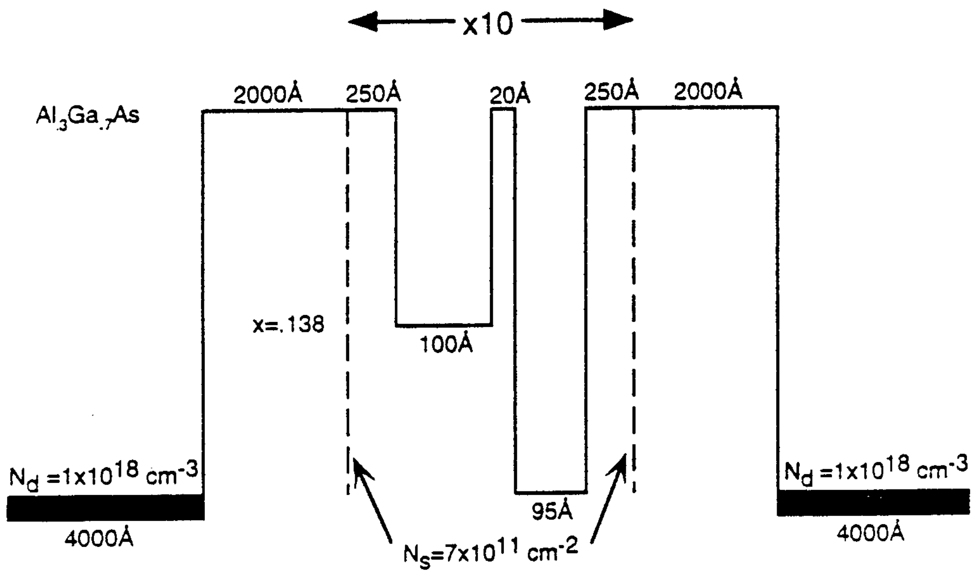


FIG. 13 Multi-quantum well sample structure (sample A) used for the observation of coherent coupling of the two upper levels.

incapable of depleting the 10 period quantum well stack. The sample bias was applied between the n+ regions, and the measured I-V characteristics were symmetric.

The low-temperature (4.2K) absorption spectra for this sample are shown in figure 14(a) with the peak positions plotted in fig. 14(b). Each scan was taken at a different applied bias (0.25V steps between adjacent curves) with the bottom curve in the figure corresponding to -3.0V, just prior to breakdown. In this case, we refer to positive bias as one that lowers the potential on the right, or substrate, side of the structure shown in fig. 13.

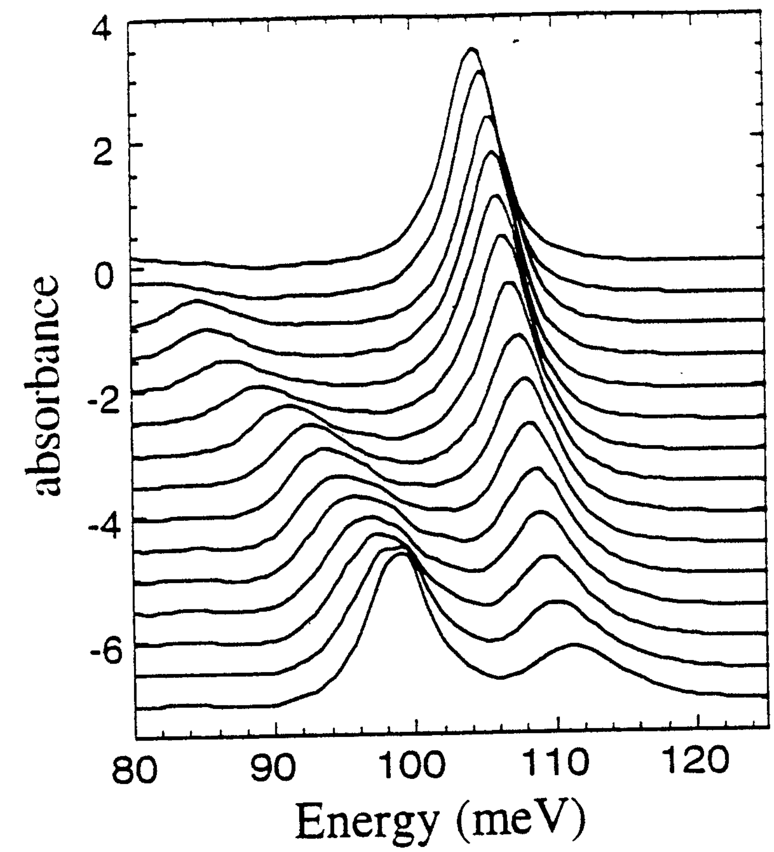
At large positive biases (top of figure 14(a)), the level in the left quantum well is much higher than the excited state in the GaAs quantum well. In this case, the coupling of levels is quite weak and only a single, spatially direct transition is observed. With increasing negative bias, the level in the left AlGaAs well is pulled down, closer to resonance, and a weak, spatially indirect, lower energy peak appears. At the anti-crossing when the levels are nicely aligned, the excited states are a superposition of the bare quantum well levels, extended across both the GaAs and AlGaAs quantum wells.

Figure 14(b) shows the measured peak positions as a function of the applied bias. Considering only the direct intersubband transition in the GaAs quantum well, we expect a transition energy that remains relatively constant with a change in applied bias, because the carriers in the well can effectively screen the electric field. Since there are no carriers in the AlGaAs well, we expect that this energy level will move linearly with applied bias as sketched in figure 14(b). These sketched lines show the expected peak positions in the absence of coupling of the upper levels, which would be the case for strongly localized states. The interaction between the upper levels leads to a peak repulsion, or "anti-crossing" of states, with a minimum peak splitting at resonance. This minimum splitting is found to be 12 meV for this structure.

b. Interference of intersubband transitions

No interference effects were observed in the bound systems because the bound intersubband transitions are not lifetime broadened. To observe interference phenomena, it is necessary to couple these wells to a continuum through a thin tunneling barrier.

To get an estimate of the tunneling rates that can be achieved in our structures, we performed transmission matrix calculations[22] to look at the transmission vs. energy curves for a single 90Å GaAs quantum well coupled to a continuum on one side by an $Al_{0.3}Ga_{0.7}As$ tunneling barrier of varying widths.



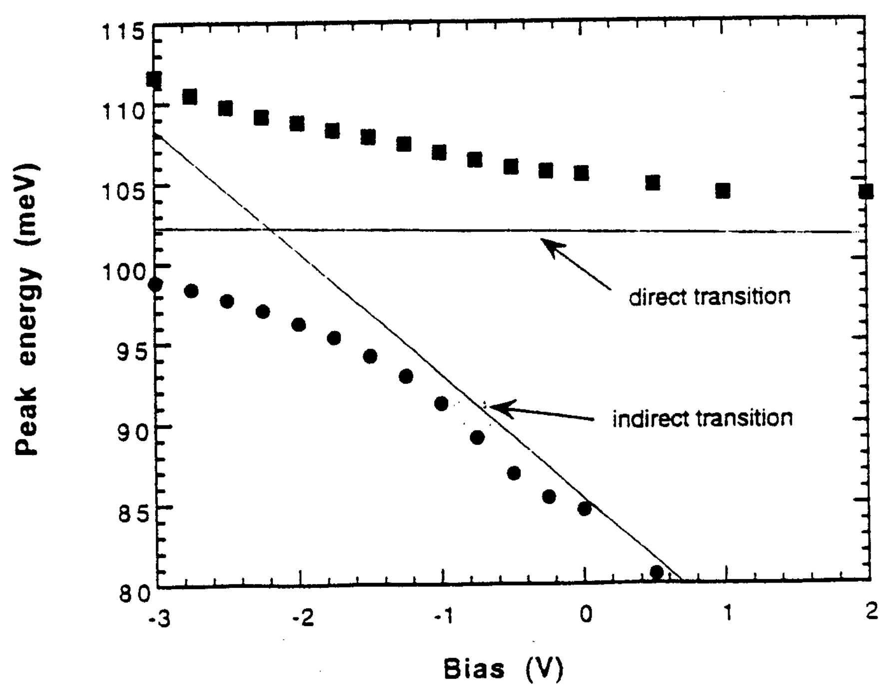


FIG. 14 (a) Intersubband absorption spectra for the coupled quantum well structure. Adjacent scans are taken at 0.25 V steps in bias and (b) Measured absorption peak positions for the coupled quantum well structure.

We used the calculated results to design and grow a sample (B) whose layer sequence is given in figure 15. In designing the sample, the layer parameters were typically chosen so that the upper levels are aligned when the sheet density of electrons in the well is approximately 5 X 10^{11} cm^{-2}. Low temperature (10 K) Hall measurements on this structure yield an electron density of 6.1 X 10^{11} cm^{-2} with mobility of 162,000 cm^2/Vs.

The Schottky gate referencing technique was used to obtain the absorption spectra shown in figure 16(a). A negative gate bias is used to deplete electrons from the quantum well, while at the same time raising the energy of the left side of the quantum well relative to the right. Figure 16(b) shows the peak positions as a function of the electron concentration showing a clear anti-crossing behavior

Comparing the minimum absorbance between the transition energies for the curve fit and the measured data, there is a reduction of absorption of almost 16% relative to the sum of Voigt profiles (a convolution of Lorentzian and Gaussian profiles).

The key to increasing the size of the interference effect is reducing the dephasing in the left quantum well. With interface roughness scattering being identified as the dominant dephasing mechanism in quantum wells, the next natural step towards reducing dephasing in the left quantum well would be to make the well wider than the 90 Å well used in sample B above. This can, however, present a problem since the strong electric fields across the left well create a triangular potential, instead of a square well potential. For wider wells, the ground state in the left well does not lie above the triangular potential, making the effective barrier for tunneling much wider. Much wider wells can be used if the Al content in the left well is graded, to offset the electric field from the dopants. In this way, the self-consistent band profile appears almost flat, even though there is a large electric field across the well (~50 kV/cm).

Figure 17 depicts the layer design for sample C, showing the grading of the left well. This grading has been done using the digital alloy technique with a 12 Å period. Hall measurements at 12 K on this sample give a sheet carrier density of 6.2 X 10^{11} cm^{-2} with a mobility of 157,000 cm^2/Vs. A self-consistent calculation of the band profile using this electron density shows that the left well potential is indeed approximately flat at zero bias conditions.

Figure 18(a) shows the zero bias absorption spectrum for sample C, which was obtained using the Schottky gate referencing technique. As a guide to the eye, center lines are drawn at the peak positions, and the asymmetry of each peak is clearly seen. This asymmetry is clearly much stronger than in the previous sample (B), indicating the presence of stronger interference between the transitions. The

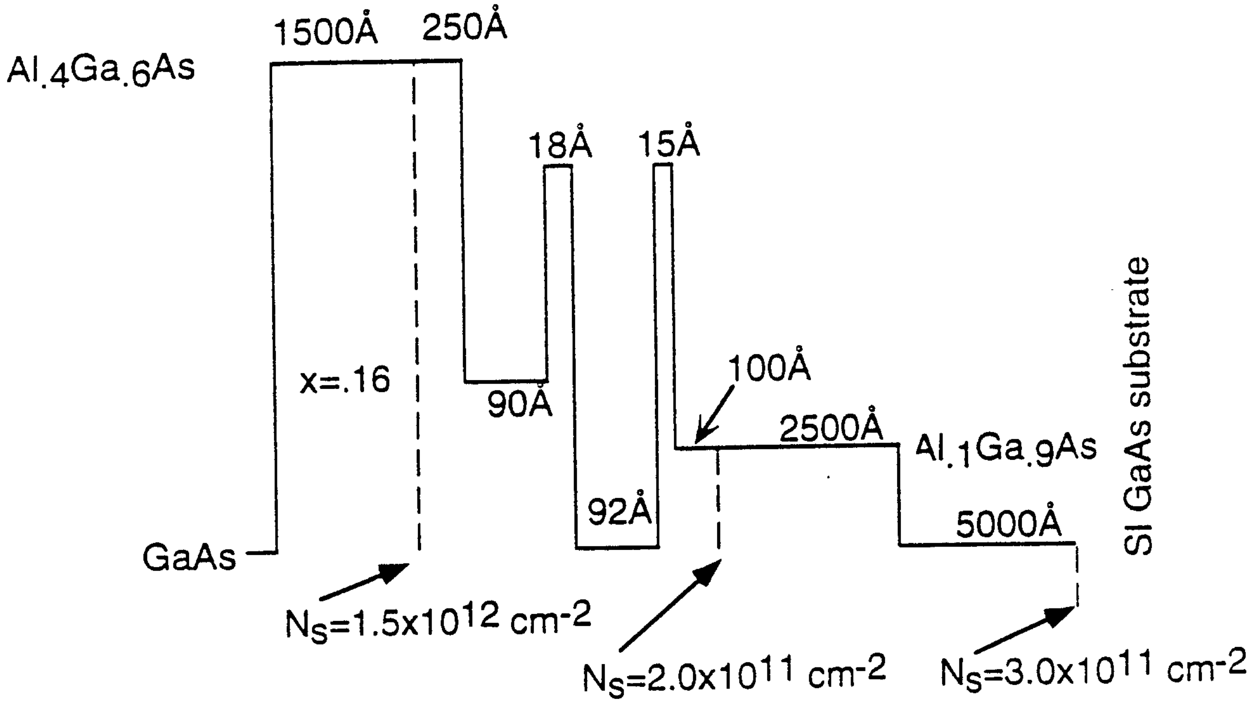


FIG. 15 Sample structure for a double quantum well coupled to a continuum (sample B).

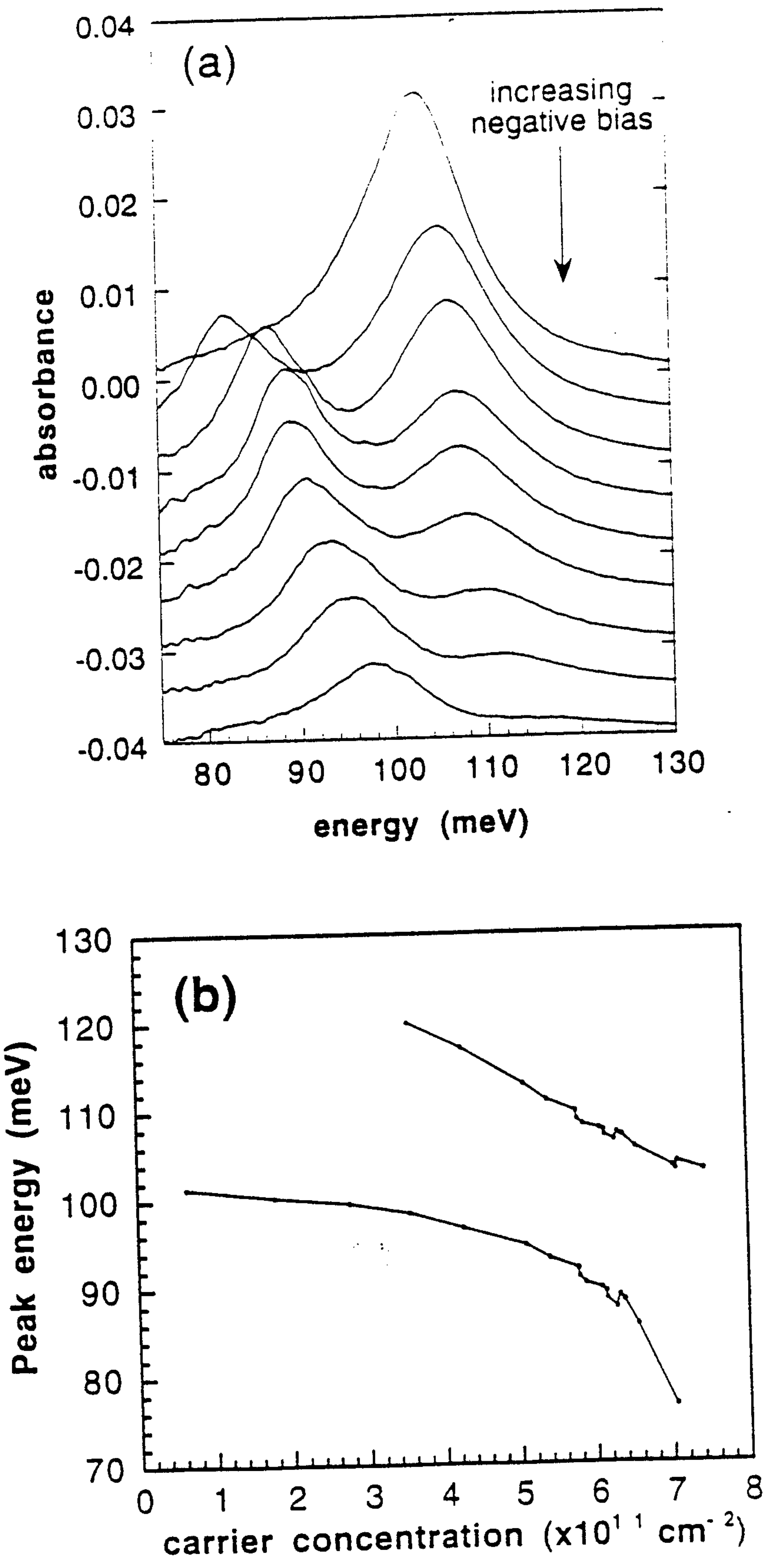


FIG. 16 (a) Absorption spectra of sample B for different Schottky gate biases. (b) Measured peak positions plotted as a function of the electron sheet density in the quantum well.

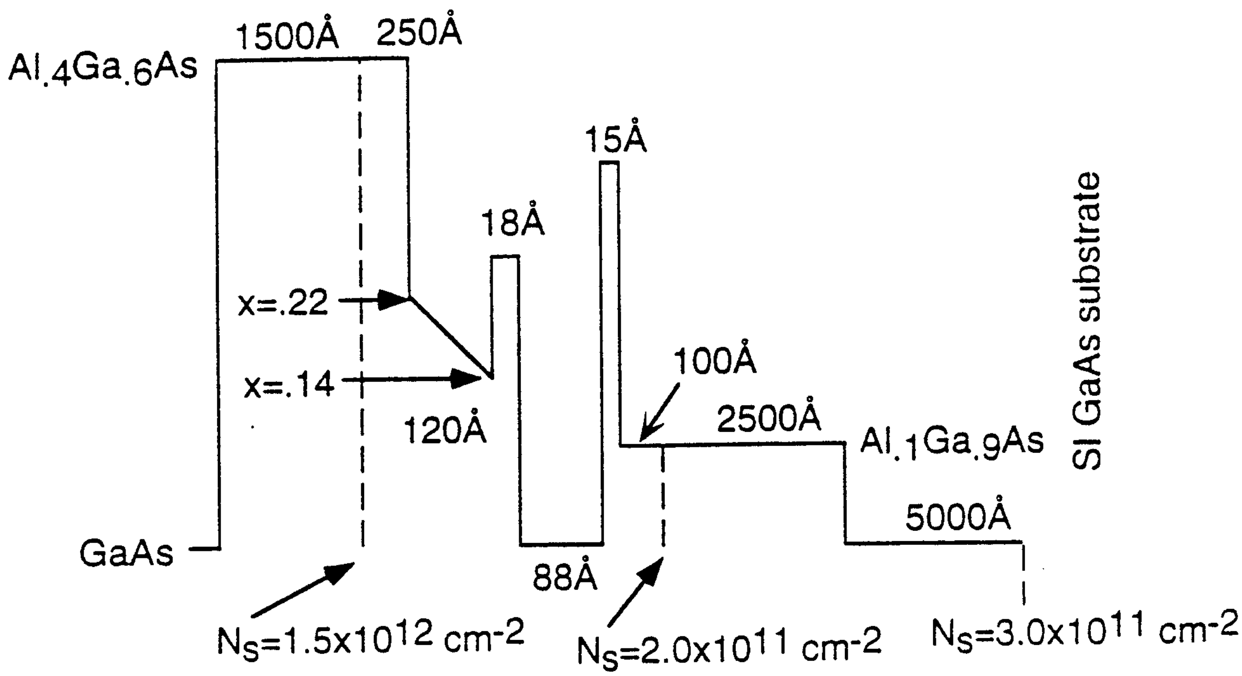


FIG. 17 Sample design for sample C, including a graded, left quantum well design to offset the electric field between the carriers and the ionized dopants.

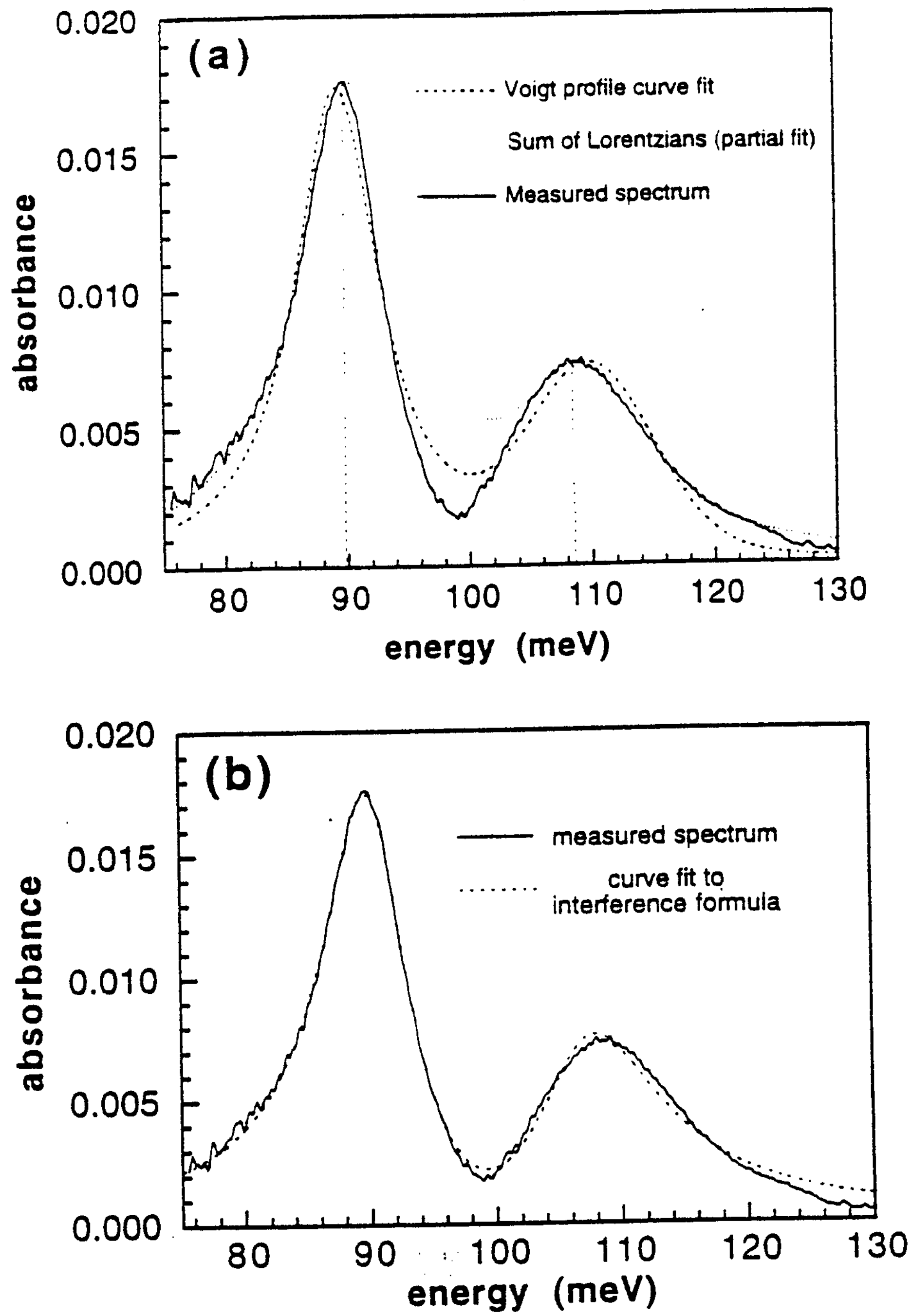


FIG. 18 Zero bias absorption spectrum for sample C with fits to (a) sum of Voigt profiles and sum of Lorentzians, and (b) the interference formula.

measured data is not fit accurately by either a sum of Voigt profiles or a sum of Lorentzians, as is seen in figure 18(a). The reduction of the absorption at energies between the two transitions is approximately 50% compared to the Voigt profile fit, and over 67% relative to the sum of Lorentzians fit.

The measured data is, however, fit extremely well, as shown in Fig. 18(b), by a more general interference formula[23]. This analysis shows that the most important difference between samples was an approximately 25% reduction in the dephasing rates for sample C, presumably a result of the increased width of the left quantum well. This reduction in dephasing makes a dramatic difference in the appearance of the absorption profiles at resonance. Further reductions in dephasing would allow an even clearer observation of interference effects and would be important for fabricating devices based on this effect.

In summary, we have demonstrated tunneling induced transparency in intersubband absorption for the first time. Absorption spectra display strong asymmetry and an absorption reduction on line center by as much as 50% compared to a sum of independent transitions. To further improve the transparency, it is necessary to reduce the coherence dephasing rates. We believe that we are currently still limited by interface roughness scattering as the dominant dephasing mechanism. Nevertheless, this result demonstrates the capability for obtaining quantum coherence effects in an electronic system largely governed by many-body interactions and inherently stronger dephasing than in atomic systems. Therefore, it represents a pivotal step towards demonstrating lasing without population inversion in intersubband transitions. This research culminated in the Ph.D. thesis of Ken Campman[24].

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4. Collaborations:

Extensive collaborations with other laboratories were pursued under this grant, including published and submitted work on 1) ultrathin GaAs cantilevers with Harvard and UCSB investigators, 2) the first stamping lithography of GaAs electronic devices with Harvard, 3) quantum confined Stark effect in parabolic wells with Erlangen, 4) wavefunction mapping in wide quantum wells with ETH Zurich, 5) measurements of Terahertz emission in Technical University, Vienna, 6) lithographically-defined quantum dots and cavities in near-surface quantum wells at Harvard and Stanford, 7) harmonic generation in point contacts with University of Munich, 8) edge state tunneling and chiral surface states in the quantum Hall effect with the UCSB Quantum Institute, 9) pressure dependence of the fractional quantum Hall effect at University of Chicago, and 10) coupled semiconductor cavity/superconductor junction devices at Harvard and at Rice Universities.

5. PERSONNEL SUPPORTED:

1. Professor Arthur C. Gossard (Principal Investigator)

Arthur Gossard received his PhD degree in Physics from University of California, Berkeley in 1960. His PhD thesis title was "Nuclear Magnetic Resonance in Ferromagnetic Materials". He was at AT&T Bell Laboratories from 1960 to 1987, with the exception of a year of research at the Centre d'Etudes Nucleaires, Saclay France from 1962 to 1963. He has been Professor of Materials and of Electrical and Computer Engineering in the University of California, Santa Barbara from July, 1987 to the present. His special interests are in the field of growth and properties of new artificially structured materials. He has 12 patents in this area and over 500 publications. He is a member of the National Academy of Engineering, a Fellow of the American Physical Society, and a former Distinguished Member of Technical Staff in Bell Laboratories.

2. Mr. Kenneth L. Campman, Graduate Student Research Assistant.

Kenneth Campman is a graduate student research assistant who worked under this grant from June, 1991 to December, 1996. He received the B.S. degree from Caltech in May, 1991 in Engineering Physics. He has been involved in the growth and the fabrication and far infrared measurement of graded, square and alloyed quantum well structures for observation of electron resonances in single and coupled wells and for observation of quantum interference in intersubband transitions. He completed his Ph.D. thesis in January, 1997 and is now employed by the Epitronics Corporation in Phoenix, Arizona.

3. Mr. Kevin Maranowski, Graduate Student Research Assistant.

Mr. Maranowski received his Bachelors Degree in Electrical Engineering from Carnegie Mellon University, Pittsburgh, in June, 1993. He joined Professor Gossard's current AFOSR program on the growth and electrical and far-infrared properties of wide electron wells in semiconductors in July, 1993. Kevin is an outstanding student and graduated from Carnegie Mellon in only three years, while achieving an overall 3.97 grade point average and holding technical industrial positions during the summers. His current work has involved the study of electron conduction over LTG GaAs/GaAs interface barriers and the observation of far infrared emission from wide graded quantum wells.

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Submitted for publication:

1. Momentum Redistribution Times of 2D Excitons Measured by Transient Resonantly Induced Intersubband Absorption. Shtrichman, I., Oiknine-Schlesinger, J., Gershoni, D., Ehrenfreund, E., Maranowski, K., Gossard, A.C. Physica (to appear)

2. Electro-Optical Probing of Envelope Wavefunctions in GaAs/AlGaAs Parabolic Quantum Well Structures. Geisselbrecht, W., Sahr, U., Masten, A., Grabner, O., Klutz, U., Forkel, M., Dohler, G.H., Campman, K., Gossard, A.C. Physica (to appear)

3. Intersubband Relaxation of Cold Electrons in a Coupled Quantum Well with Subband Spacing Below. Heyman, J.N., Barnhorst, J., Unterrainer, K., Craig, K., Williams, J., Sherwin, M.S., Campman, K., Gossard, A.C. Physica (to appear)

4. Josephson junction oscillators as probes of electronic nanostructures. A.S. Adourian, Scott Yang, R.M. Westervelt, C.M. Marcus, K.L. Campman, and A.C. Gossard. Phys. Rev. B15 (to appear).

5. Edge state tunneling in the quantum Hall effect. P.J. Turley, D.P. Druist, E.G. Gwinn, K. Maranowski, K. Campman and A.C. Gossard. Phys. Rev. B15 (to appear).

6. Direct Measurement of the Destruction of Charge Quantization on a Quantum Dot. D.S. Duncan, C. Livermore, R.M. Westervelt, K.D. Maranowski, A.C. Gossard. Science (to appear)

7. Subband dependent density of states in asymmetric quantum wells with in-plane magnetic fields. G. Salis, B. Rustaller, K. Ensslin, K. Campman, K. Maranowski, A.C. Gossard. (submitted to Phys. Rev. B)

7. INTERACTIONS/TRANSITIONS:

a. Presentations at meetings, conferences

Momentum Space Redistribution of Resonantly Photoexcited Excitons in GaAs/AlGaAs Superlattices. Strichman, I., Gershoni, D., Ehrenfreund, E., Maranowski, K., Gossard, A.C., Intersubband Transitions in Quantum Wells '97, Tainan, Taiwan, Dec. 14, 1997.

Electrically Excited Terahertz Emission from Parabolic Quantum Wells. Maranowski, K.D., Gossard, A.C., Unterrainer, K., Gornik, E. Intersubband Transitions in Quantum Wells '97, Tainan, Taiwan, Dec. 14, 1997.

Momentum Redistribution Times of 2D Excitons Measured by Transient Resonantly Induced Intersubband Absorption. Shtrichman, I., Oiknine-Schlesinger, J., Gershoni, D., Ehrenfreund, E., Maranowski, K., Gossard, A.C. International Conference on Modulated Semiconductor Structures, Santa Barbara, CA, July 15, 1997.

Electrically Excited Terahertz Emission from Plasma Oscillations in Parabolic Quantum Wells. Maranowski, K.D., Gossard, A.C., Unterrainer, K., Gornik, E. International Conference on Modulated Semiconductor Structures, Santa Barbara, CA, July 15, 1997.

Electro-Optical Probing of Envelope Wavefunctions in GaAs/AlGaAs Parabolic Quantum Well Structures. Geisselbrecht, W., Sahr, U., Masten, A., Grabner, O., Klutz, U., Forkel, M., Dohler, G.H., Campman, K., Gossard, A.C. International Conference on Modulated Semiconductor Structures, Santa Barbara, CA, July 15, 1997.

Few-Cycle THz Emission from Intersubband Plasmon Oscillation in Parabolic Wells. Unterrainer, K., Kersting, R., Heyman, J.N., Strasser, G., Maranowski, K.D., Gossard, A.C. International Conference on Modulated Semiconductor Structures, Santa Barbara, CA, July 15, 1997.

A Tunable Antenna-Coupled Intersubband Terahertz. Cates, C., Briceno, J.B., Williams, J.B., Sherwin, M.S., Campman, Gossard, A.C. International Conference on Modulated Semiconductor Structures, Santa Barbara, CA, July 15, 1997.

Measurements of Far-Infrared Intersubband Absorption Linewidths in GaAs/AlGaAs Quantum Wells as a Function of Temperature and Charge Density. Williams, J.B., Craig, K., Sherwin, M.S., Campman, K., Gossard, A.C. International Conference on Modulated Semiconductor Structures, Santa Barbara, CA, July 15, 1997.

Intersubband Relaxation of Cold Electrons in a Coupled Quantum Well with Subband Spacing Below. Heyman, J.N., Barnhorst, J., Unterrainer, K., Craig, K., Williams, J., Sherwin, M.S., Campman, K., Gossard, A.C. International Conference on Modulated Semiconductor Structures, Santa Barbara, CA, July 15, 1997.

GaAs/AlGaAs self sensing cantilever for cryogenic scanning probe microscopy. R.G. Beck, M.A. Eriksson, R.M. Westervelt, K.D. Maranowski, A.C. Gossard. American Physical Society Meeting, March, 1997, Paper B13.09

Effect of Time Reversal Symmetry Breaking on Non-Linear Transport in a Ballistic GaAs Quantum Dot. M. Switkes, A. Huibers, C.M. Marcus, K. Campman, A.C. Gossard. American Physical Society Meeting, March, 1997, Paper [B13.12]

Weak Localization and Dephasing in Chaotic Semiconductor QuantumDots. A. Huibers, M. Switkes, C.M. Marcus, K. Campman, A.C. Gossard. American Physical Society Meeting, March, 1997. American Physical Society Meeting, March, 1997, Paper [C13.07]

Dissipation-Driven Superconductor-Insulator Transition in a Two-Dimensional Josephson Junction Array. A.J. Rimberg, T.R. Ho, C. Kurdak, John Clarke, K.L. Campman, A.C. Gossard. American Physical Society Meeting, March, 1997, Paper [E10.09]

Multi-channel optically-detected terahertz resonance spectroscopy of magnetoexcitons. J. Cerne, M.Y. Su, A. Gutierrez, M.S. Sherwin, M. Sundaram, A.C. Gossard (Materials Department, University of California, Santa Barbara), H. Sakaki. American Physical Society Meeting, March, 1997, Paper [E12.11]

Coulomb Blockade Peak Spacing Distributions for B = 0 and B \ne 0 in Quantum Dots. S.R. Patel, S.M. Cronenwett, C.M. Marcus (Department of Physics, Stanford University), K. Campman, A.C. Gossard. American Physical Society Meeting, March, 1997, Paper [F14.04]

A Voltage-Tunable Quantum Well Detector for Terahertz Radiation. G. Briceño, J. B. Williams, M. S. Sherwin, K. Campman, A. C. Gossard. American Physical Society Meeting, March, 1997, Paper [G12.06]

Dynamic localization, absolute negative conductance and multi-photon assisted tunneling. S. Zeuner, S.J. Allen, K.D. Maranowski, A.C. Gossard. American Physical Society Meeting, March, 1997, Paper [N12.04]

Low Temperature Magnetometry Using 100 nm Thick Micromechanical Cantilevers. J.G.E. Harris, D.D. Awschalom, K.D. Maranowski, A.C. Gossard. American Physical Society Meeting, March, 1997, Paper [N19.06]

Evidence for a Spin Transition in the $\nu=2/5$ Fractional Quantum Hall Effect. W. Kang, J.B. Young (University of Chicago), S.T. Hannhas, E. Palm, K. Campman, A. Gossard (UC Santa Barbara) . American Physical Society Meeting, March, 1997, Paper [Q12.03]

Universal Conductance Fluctuations of Elastic Cotunneling in Coulomb-Blockaded Quantum Dots. S.M. Cronenwett, S.R. Patel, C.M. Marcus, K. Campman, A.C. Gossard (Materials Department, UCSB) . American Physical Society Meeting, March, 1997, Paper [Q13.11]

Probing Luttinger Liquids with Edge State Tunneling. D. P. Druist, P. J. Turley, E. G. Gwinn, K. Maranowski, K. Campman, A. C. Gossard (QUEST and ECE, University of California, Santa Barbara) . American Physical Society Meeting, March, 1997, Paper [R12.02]

Resonant Tunneling Through a Point Contact in the FQHE Regime. P. J. Turley, D. P. Druist, E. G. Gwinn, K. Maranowski, K. Campman, A. C. Gossard. American Physical Society Meeting, March, 1997, Paper [R12.03]

Conductance Resonances in a Two-Dimensional Electron Gas Interferometer. J.A. Katine, M.A. Eriksson, A.S. Adourian, E.J. Heller, R.M. Westervelt, K.L. Campman, A.C. Gossard. American Physical Society Meeting, March, 1997, Paper [R15.07]

Period-Doubling in the Intersubband Dynamics of Quantum Wells Driven by Intense Terahertz Fields. M. S. Sherwin, J. B. Williams, F. A. Hegmann, K. Campman, A. C. Gossard. American Physical Society Meeting, March, 1997, Paper [S13.12]

Electron Spin Polarization in GaAs Quantum Wells Measured by Ga Optical Pumping NMR. Y.-Q. Song, B. M. Goodson, K. D. Maranowski, A. C. Gossard. American Physical Society Meeting, March, 1997, Paper [O14.05]

b. Consultative and advisory functions:

Member, Advisory Committees of Materials Research Laboratory, University of Illinois; Materials Research Center, Lawrence Berkeley Laboratory, Berkeley, CA.; Materials Science Dept., University of Utah.

Chairman, Advisory Committee, Quantum Institute, University of California, Santa Barbara

Member, Review Board for Programs and Funding in Canadian Condensed Matter Physics, 1997.

Member, National Academy of Public Administration Review Panel for Space Vacuum Epitaxy Center, University of Houston, 1997

c. Transitions:

In collaboration with Epi Products, Inc., the leading manufacturer of MBE semiconductor manufacturing equipment in the United States , we served as the main training facility for new users of Epi Products Gen II MBE manufacturing equipment.

Design and modeling of graded structures for the possible production of quantum cascade lasers were performed for the Spire corporation under a project headed by Dr. Kurt Linden. Resonant tunneling diodes designed in our lab were grown by MOCVD at the Spire corporation.

Discussions were held with Dr. Scott Chalmers, of the company Filmetrics for exchange of technology on atomic absorption in-situ monitoring of molecular beam fluxes during epitaxial crystal growth and in-situ reflectivity spectral measurements during MBE film growth.

8. NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES:

none

9. HONORS AND AWARDS:

Arthur C. Gossard:

Fellow, American Physical Society, 1970

Distinguished Technical Staff Member Award, AT&T Bell Laboratories, 1983

Oliver F. Buckley Condensed Matter Physics Prize, American Physical Society, 1984
Received jointly with H. L. Störmer and D. C. Tsui for the discovery of fractional quantization of the Hall effect.

Membership in National Academy of Engineering, 1987.

Humboldt Foundation Senior Fellowship, 1996.